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Deep Space Network Radio Science System for Voyager Uranus and Galileo Missions

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This article presents an overview of major new requirements, challenges and conceptual designs for the DSN Radio Science System in the 1985 to 1988 period. The Voyager Uranus encounter is being supported with larger combined aperture, higher sample rate, and a centrally controlled network The Galileo mission will be provided with a high resolution S-Band Faraday rotation detection capability and a high-stability Doppler system with X-Band uplink for gravitational wave search.

I. Introduction

The Deep Space Network (DSN) Radio Science System is a collection of equipment, software, and procedures that enables the DSN to function as an instrument supporting spacecraft radio science experiments. The System has been used by past and present missions to receive and record spacecraft carrier signals in occultation and other propagation experiments. The recorded signals have been analyzed to produce scientific results characterizing planet atmosphere, ionosphere, ring structure, gravity field, solar wind, etc. From 1987, the System will further provide two new capabilities to support the Galileo mission: a Faraday rotation detection capability for mapping the Jovian ionosphere and a very stable two-way Doppler capability for gravitational wave search.

The purpose of this article is to present an overview of major requirements, challenges, and conceptual designs for the DSN radio science system as planned for the 1985 to 1988 period. In this period, the Voyager Uranus and Galileo missions require enhancement of the System beyond its existing capability. The enhanced capability is expected to meet the needs of all other missions as well. In 1989, the Voyager mission will encounter planet Neptune, requiring additional aperture to receive even weaker signals

Two types of data are usually used by the radio scientists. One type is acquired by the open-loop receivers and recorded as broad-band data. The science results mentioned before are mainly derived from this type of data. The other type is the traditional radiometric data containing Doppler and range information. The radiometric data are acquired by the closed-loop receivers and are produced regularly by the DSN Tracking System. Description of the DSN Tracking System can be found in other articles of the *TDA Progress Report*. This article will address the open-loop data system only.

Section II describes the system configuration which is presently being implemented in the network to support

Voyager Uranus occultation experiments. This configuration contains equipment with improved performance, able to be centrally controlled, and capable of simultaneously receiving and recording the same spacecraft signal at multiple antennas.

Section III describes the configuration which will be implemented in the network to support the Galileo Faraday rotation experiment in 1988. This configuration contains new phase calibration and real-time verification capabilities.

Section IV describes the configuration planned for the Galileo gravitational wave experiment. This configuration strives to achieve the highest degree of phase stability ever attempted by a tracking station. It will contain the first DSN X-band transmitter and a set of highly stable receiving and calibrating equipment implemented on the new 34-m High Efficiency antenna.

II. Configuration for Voyager Uranus Occultation Experiments

A. The Challenge

The Voyager radio science occultation experiments at Uranus encounter will attempt to characterize the atmosphere of the planet and the structure of its rings. The objective of DSN support is similar to that at the Saturn encounter: recording spacecraft carrier signals during occultations by the rings, the planet and its atmosphere. The Uranus encounter experiments, however, present new challenges to the DSN. First, the signal from the Uranus distance will be weaker. Second, by the time of Uranus encounter, the DSN will have a completely different operational network, the Mark IVA Network, with which the radio science system equipment must interface. Third, some harmonic noises and record gaps that degraded data return at Saturn encounter must be eliminated to make the experiments successful.

B. Implementation at Canberra Complex

Because Uranus is visible mainly at encounter from the southern hemisphere, the DSN is implementing the configuration given in Fig. 1 at the Canberra Deep Space Communication Complex (DSCC) in Australia. This complex is able to cover the entire Uranus occultation experiment. Three antennas will be receiving signals: the 64-m Deep Space Station (DSS) 43, the 34-m DSS 42, and the 64-m radio telescope at the Australian Parkes Observatory. The first two antennas will receive both X-band and S-band signals while the third antenna will receive only the X-band signal, due to cost consideration. The combined aperture provides an increase in gain-noise ratio (G/T) of approximately 3 dB in X-band reception and 1 dB in S-band reception relative to the performance of a single DSS 43, which was the only station available for radio science at the Voyager Saturn encounter.

As shown in Fig. 1, the system involves equipment in four different geometrical areas: the antennas at Canberra, the antenna at Parkes, the Signal Processing Center (SPC) at Canberra, and the Network Operations Control Center (NOCC) at JPL.

1. **The antennas at Canberra.** DSS 43 and DSS 42 will each have X-Band and S-Band maser amplifiers with approximately 20 K noise temperature, and identical downconverters with 300 MHz intermediate frequency (IF) outputs. Two channels from each antenna are transmitted to the SPC for further down-conversion and processing.

2. **The Signal Processing Center.** The four signals from the Canberra antennas are converted to video frequencies and filtered to 25 kHz bandwidth each. These signals are then sampled in the DSCC Spectrum Processing Subsystem (DSP) at a rate of 50 ksps (kilo samples per second) per channel, 8 bits quantized, and are recorded on magnetic tapes at a total rate of 200 ksps. These tapes are called the Original Data Record (ODR) which will be shipped after the encounter to the investigators for analysis.

The Spectrum Processing Subsystem (DSP) is the action center of the radio science system. Under the supervision of the DSCC Monitor and Control Subsystem (DMC), the DSP configures itself and tunes the frequencies of the receivers at DSS 43 and DSS 42 according to control messages and frequency predictions received from the NOCC. It also records the system temperature (T_{op}) and the received carrier signal level (P_c) measured by the Precision Power Monitor (PPM).

The sampled signals that are ready to be written on a magnetic tape will also be converted back to analog signals and transmitted to the Spectral Signal Indicator (SSI), a digital spectrum analyzer having a resolution bandwidth as narrow as a fraction of a Hertz. The SSI will display the signal spectrum locally and will also send digital spectral data to the DSP which relays the data to NOCC for display to the mission analysts.

3. **The Network Operations Control Center.** At the NOCC, the spectral data will be displayed by the NOCC Radio Science-VLBI Subsystem (NRV). The display will be observable in the Mission Support Area where Voyager radio science analysts will be able to monitor the performance of data acquisition at the complex and suggest changes in receiver tuning in case the observed frequency of the received signal changes unexpectedly.

The NOCC also contains the Network Support Subsystem (NSS) which generates frequency and pointing angle predictions and the mission sequence of events. This information is transmitted to the SPC to configure the equipment, point the antenna, and tune the receiver frequencies in a timely manner.

4. **Performance improvement**. There will be significant improvement of system performance compared with the performance at the Voyager Saturn encounter. The spurious noise level of the receiver has been reduced from -40 dBc (dB relative to the carrier) to lower than -50 dbc by redesigning the local oscillator multiplier chain. The sampling aperture jitter has been reduced from over 100 nsec to less than 5 nsec by hardware modification. More visibly, the new Spectrum Processing Subsystem (DSP) will be equipped with computer compatible magnetic tape drives with error detection capability that promises to reduce data recording errors from approximately 1% in the pervious system to a thousandth of 1%. The Subsystem also uses an improved computer, a Modcomp Classic replacing the Modcomp II, to control sampling and recording at higher speed and with better reliability.

5. **Parkes array**. The Parkes 64-m antenna will be equipped with an X-Band maser amplifier with an approximately 20 K system temperature, an RF to IF converter, and a Mark III Occultation Data Assembly (ODA) equipped with an IF to video converter. The received carrier signal is down-converted and recorded on tape as an Original Data Record.

The Original Data Records containing carrier signal information received at DSS 43, DSS 42 and the Parkes antenna will be shipped to the laboratories of the investigators where the three streams of data will be synchronized, combined and analyzed.

6. **Wideband backup**. Since the occultation experiments are a one-time event lasting only 400 minutes, a wideband backup system is also implemented at the DSS 43 and DSS 42 antennas. The backup system receives the X-Band and S-Band signals at both antennas at a total bandwidth of 8 MHz and records the signals on tape These backup tapes will be shipped to JPL to be filtered, reformatted and recorded in standard radio science format

C. Baseline Radio Science Configuration at Goldstone and Madrid Complexes

A baseline radio science system still exists at both the Goldstone and Madrid complexes which will not be involved in Voyager Uranus occultation experiments. The baseline system includes data acquisition from the 64-m DSN antenna only, receiving 4 channels of signals coherently and recording at a total data rate up to 200 ksps, 8 bits per sample. Various channel bandwidths from 100 Hz to 100 kHz can be selected for operation under the constraint of the total data rate. The 4 channels have often been used to receive X-band and S-band signals with right and left circular polarizations (RCP/LCP) simultaneously The Canberra complex can be easily restored to this baseline configuration after the Voyager Uranus encounter. The capabilities to measure system temperature, carrier signal power and the signal spectrum are also available in the baseline system.

III. Configuration for Galileo Faraday Rotation Experiment

A. The Challenge

Besides regular occultation experiments similar to those conducted by Voyager, the Galileo mission will conduct two additional radio science experiments: a Faraday rotation experiment and a gravitational wave search. The Faraday rotation experiment will measure the rotation of a linearly polarized S-Band carrier signal when it propagates through the charged particle and magnetic fields of the Jovian environment. The objective is to characterize the spacial and temporal distribution of the magnetic and charged particle fields. The resolution required by the investigation to characterize the distribution is 5 deg or better, observed over time periods ranging from 1 min to 10 hours. Simultaneous reception of an X-band RCP coherent signal will permit separation of the charged particle effect from the magnetic field effect.

In addition, the DSN is required to show the presence of the linearly polarized signal in real time to verify the proper functioning of the data acquisition system.

B. Planned Implementation

To be consistent with the total error budget for the experiment the DSN is planning to design the data acquisition system for a 2.3-deg accuracy and to calibrate the earth ionospheric effect to 1.0 deg. This section will only describe the data acquisition system. The DSN plans to calibrate the earth ionosphere using signals from thr NAVSTAR Global Positioning System (GPS) satellites. Description of the GPS system is beyond the scope of this article.

1. **Data flow**. The S-band data flow through the system is shown in Fig. 2 The X-band acquisition data flow uses the standard radio science technique, and will not be discussed further. The linearly polarized S-band signal received by the 64-m antenna will first be separated in the microwave Ortho Mode Junction (OMJ) into RCP and LCP components. Through two independent but identically configured channels, the

RCP and LCP components will be amplified in the maser amplifiers, down-converted to 300 MHz IF, and transmitted from the antenna to the control room in the SPC. There, both signals will be down-converted to narrow band video frequencies and will be digitized and recorded in the Spectrum Processing Subsystem (DSP). The recorded data will contain information that allows the investigators to measure the relative phase of the RCP and the LCP components of the carrier. The time history of this measurement indicates the received polarization angle vs time. Subtraction of the spacecraft orientation yields the needed results: the change of Faraday rotation angle through time.

There will be a major design change in the tuning of the receiver frequency compared with the Voyager configuration. The receiver frequencies will be tuned at the second local oscillator inside the control room, approximately at 300 MHz. It will no longer be tuned at the first local oscillator in the antenna at microwave frequencies. This change permits a fixed local oscillator with a higher frequency stability to be used at the RF-to-IF converter, improving the effective stability of the overall receiving system. This improved stability will be necessary for supporting the gravitational wave search to be discussed later.

2. **Real-time verification**. The rate and residual (difference between observed and predicted angles) of the polarization angles will be measured in real time by digitally processing the RCP and LCP signals in the Spectrum Processing Subsystem. The measured angle rate will approximate the spin rate of the Galileo spacecraft.

The measured rate and residuals of the polarization angle will be displayed at the complex, the NOCC, and the Mission Support Area. They will also be recorded on the Original Data Record for use by the investigators.

3. **Phase calibration**. The recorded data cannot avoid containing errors introduced by the receiving system when the two signals propagate through identical but separate receiver channels. To keep the error below 2.3 deg over 10 hr, it is necessary to calibrate the variation of phase difference between the two channels.

Since the LCP and RCP signals have the same frequency when separated and since the local oscillators that down-convert the two signals have the same source frequency, the differential phase between the two channels is expected to be small and stable. Indeed a recent test conducted at the 64-m antenna at Madrid has demonstrated that, when the antenna was stationary, the phase difference between the RCP and the LCP channels from the RF to recording remained within 1×10^{-15} in terms of fractional frequency stability relative to S-band. This is equivalent to 1 deg for every 20 min. Another test conducted in the laboratory at JPL has demonstrated the phase difference between the two channels in the control room, from 300 MHz IF to video frequency output, to remain within 1 deg over 4 hr. These tests indicated that at least the control room equipment is stable over long hours within a small fraction of the total error budget. To maintain precise knowledge of the phase errors of the system over time, it is only necessary to calibrate the front end portion of the system, including the microwave amplifiers, down-converters and the long cables from the antenna to the control room

The phase calibration scheme planned for this experiment will calibrate the angle of polarization of the received signal and the phase variation of the RCP and LCP channels through time. As indicated in Fig. 2, a stabilized S-band calibration signal which is generated by the Phase Calibration Generator (PCG) assembly will be injected into a linearly polarized microwave coupler. This coupler will be located where the RCP and the LCP components of the downlink signal are not yet separated, so that both RCP and LCP channels will receive the same calibration signal. The PCG generates high stability calibration signals by bringing a frequency reference from the hydrogen maser to the antenna, using a phase stabilized cable.

The hydrogen maser is the source of all frequencies and times used at the complex, making coherent all parts of the radio science system at the complex. A phase comparator will be used to extract the calibration tones imbedded in the signals transmitted from the antenna to the control room and to keep track of the phase changes through time. These detected changes are then sent to the Spectrum Processing Subsystem for processing, formatting and recording. As presently conceived, the phase comparator will be implemented with existing VLBI equipment in the complex: a Digital Tone Extractor preceded by an IF to Video converter

This calibration is expected to reduce the polarization angle measurement error contributed by the front-end portion and the long transmission cables to less than 1.8 deg. By keeping the error from IF to recording within 1 deg, the total error can be maintained within the 2.3-deg allowance assigned to the DSN. This error budget serves as a starting point for system design. A detailed system design is under way, including a more precise definition of achievable system error and the contribution of major assemblies. The errors will finally be measured before the system is delivered to the network in early 1987.

IV. Galileo Gravitational Wave Experiment

A. The Challenge

The Galileo spacecraft is the first spacecraft to carry a transponder with an X-Band receiving capability to receive X-Band uplink signals and return X-Band and S-Band signals coherently. Since an X-Band signal experiences much less phase noise then an S-Band signal when propagating through charged particles, a two-way Doppler system with an X-Band uplink can detect a much smaller phase perturbation than can the same system with an S-Band uplink. The Galileo mission plans to take advantage of the X-Band uplink capability and the very long round-trip light time to search for gravitational waves (G Waves, for short). Detection of the G Waves requires the Doppler system to be stable to a few parts 10^{-15} or better in terms of fractional frequency stability ($\Delta F/F$), averaged over approximately 1000 sec. After examining technical feasibilities and costs, it was decided to implement X-Band uplink capabilities at the new 34-m High-Efficiency (HE) antennas, and to design its equipment so that the fractional frequency stability of the total ground system, including uplink and downlink, could be better than 5×10^{-15}. It will be the first time the DSN implements an X-band uplink capability, and the first time such a high level of phase stability is attempted.

B. Planned Implementation

1. **The configuration**. The planned configuration to support this experiment is depicted in Fig. 3. It includes an X-Band exciter and an X-Band transmitter in the uplink, with a Digitally Controlled Oscillator (DCO) controlling the uplink frequency. In the downlink it includes X-band and S-band low-noise amplifiers, open-loop receivers, and the Spectrum Processing Subsystem (DSP) that controls and calibrates the downlink system. The DSP also digitizes, processes, and records the data. The system also includes the Phase Calibration Generator (PCG) that delivers local oscillator frequencies and X-Band phase calibration signals to the antenna, with stability approaching that of the Hydrogen maser standard. The S-band signal is received for media calibration only. Since the S-band channel is expected to be stable enough for media calibration, no phase calibration is planned for the S-band channel.

Both uplink and downlink data are needed by the investigators to determine the Doppler frequency. The uplink data will contain frequencies commanded by the uplink DCO. The downlink data will include signals received in X-Band and S-Band, the local oscillator frequency of the receiver, and the phase calibration data for the X-band receiver channel.

2. **Error budget**. A detailed performance analysis was conducted in 1984 to see if the 5×10^{-15} stability goal for the ground station is achievable. The potentials of every element in the system were examined according to the actual measurements of prototype equipment under advanced development, experience on similar hardware, computer simulation, and theoretical calculations. The result of the design analysis showed that with careful design and testing on each component, the 5×10^{-15} overall stability goal is indeed achievable. The error contributed by each element of the system is estimated in Table 1 in terms of fractional frequency standard deviation (square root of Allan variance of $\Delta F/F$ relative to X-band and averaged over 1000 sec). The basis for each estimate is also indicated in Table 1

When implemented, the stability of the ground system will be measured in the following ways. The stability of the hydrogen maser frequency standard and the stability of the up- and downlinks combined, excluding the hydrogen maser and the antenna, will be measured separately. The stability of the station, including the hydrogen maser and the up- and downlinks but excluding the antenna, will then be estimated from the results of the two measurements These measurements do not require a spacecraft, a test translator will be used instead to convert uplink frequencies to downlink frequencies. The contribution of the antenna structure to the instability of the station can only be estimated by conducting a Doppler test with the spacecraft when the spacecraft and the media are quiet.

3. **Further work** A detailed system design was developed in 1985 in which the error budgets reported here were confirmed and methods of testing for the system and the contributing subsystems were defined The prototype equipment is being built. It will undergo a ground system test in May 1986 at DSS 13 The station will be used in a flight demonstration with the Galileo spacecraft in August 1986. The results will be reported in the future.

Table 1. Error budget for Galileo gravitational wave search: 34-m HEF antenna contribution with X-band uplink and X-band downlink

Square root of Allan variance of $\Delta F/F$ relative to 8.4 GHz averaged over 1000 sec, $\times 10^{-15}$		
1. Hydrogen maser		1.0[a]
2. Uplink		2.8
Exciter and transmitter (with phase feedback)	2.7[b]	
microwave	0.5[c]	
3. Downlink		3.0
Microwave	0.5[c]	
Phase calibration	2.2[d]	
IF-video conversion	2.0[d]	
Digitization	0.1[d]	
4. Antenna structure (uplink and downlink, 10 mph wind)		1.4[e]
Total Root Sum Squared (RSS)		4.5

[a]From measurement of existing units
[b]From measurement of advanced development units
[c]Analytical result
[d]Analysis of performance of similar or prototype units
[e]Computer simulation

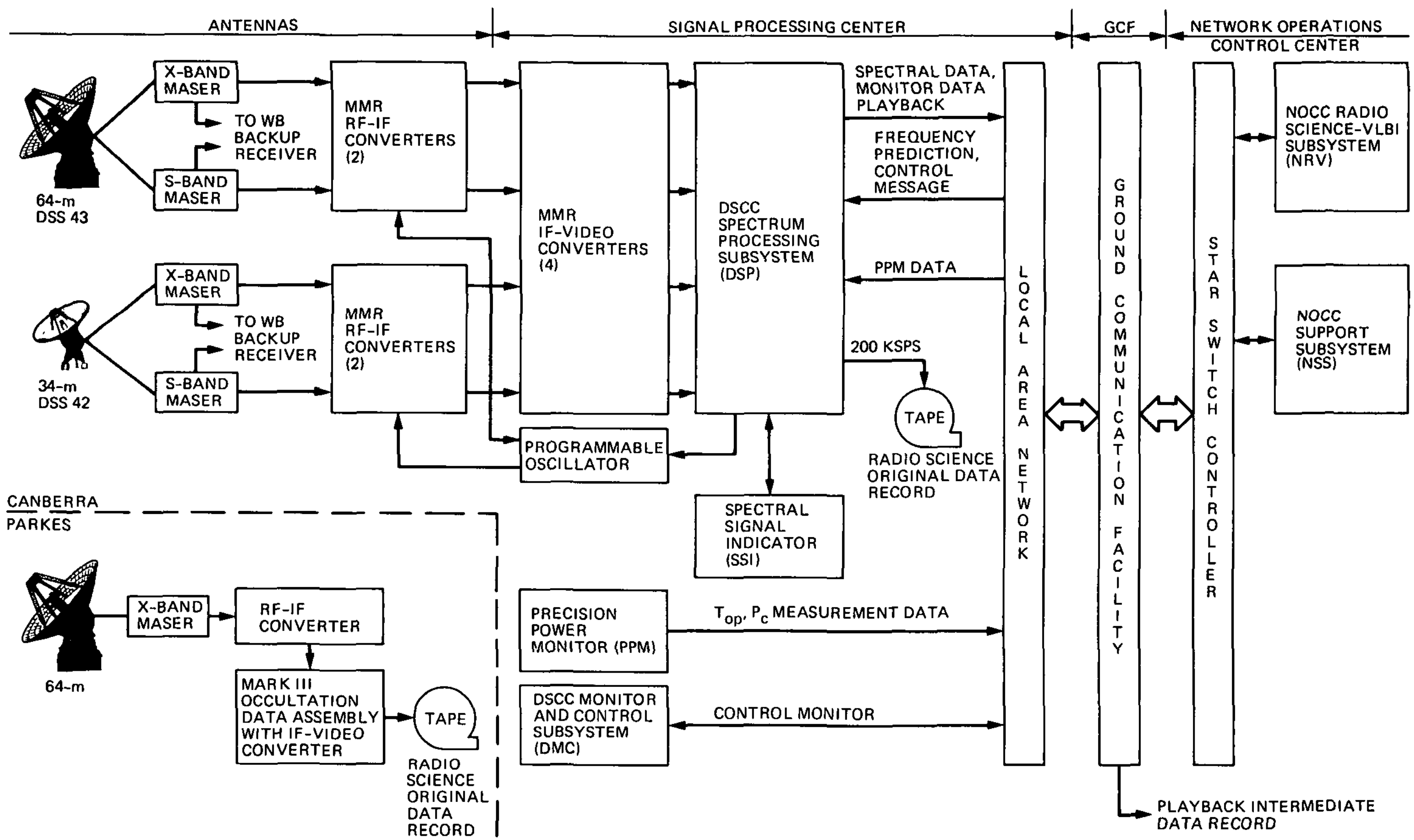
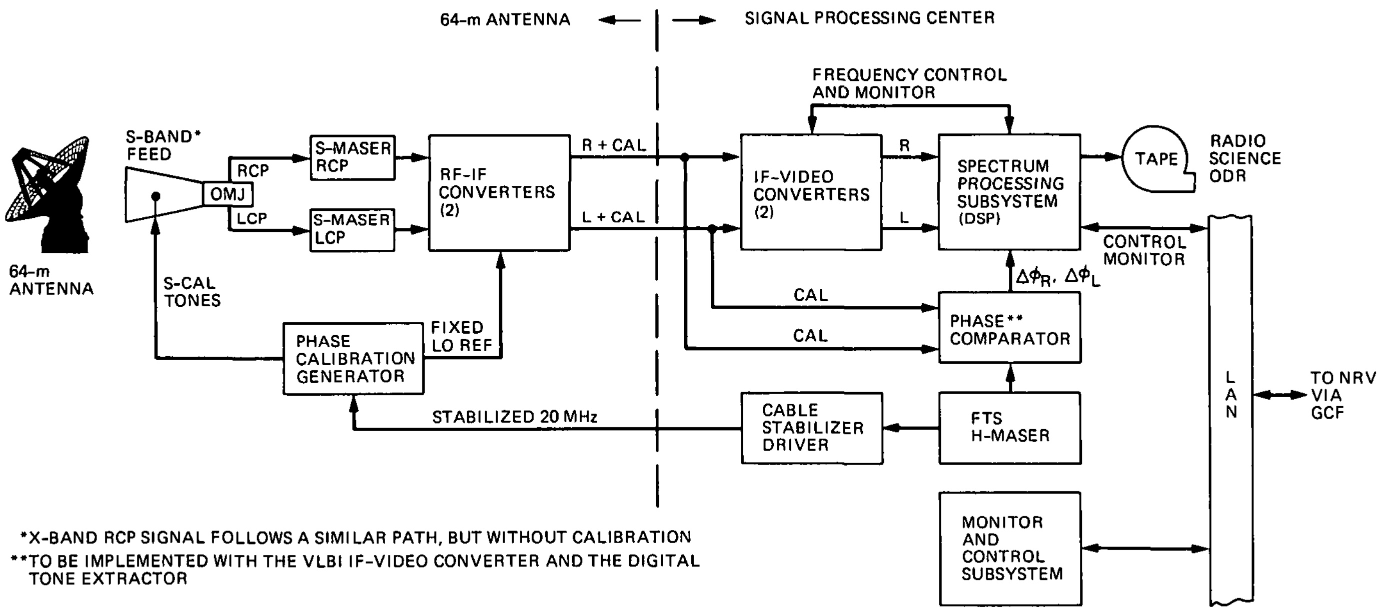


Fig. 1. DSN radio science data flow for the Voyager Uranus occultation experiments, Canberra DSCC



*X-BAND RCP SIGNAL FOLLOWS A SIMILAR PATH, BUT WITHOUT CALIBRATION

**TO BE IMPLEMENTED WITH THE VLBI IF-VIDEO CONVERTER AND THE DIGITAL TONE EXTRACTOR

Fig. 2. DSN radio science data flow for the Galileo Faraday rotation experiment

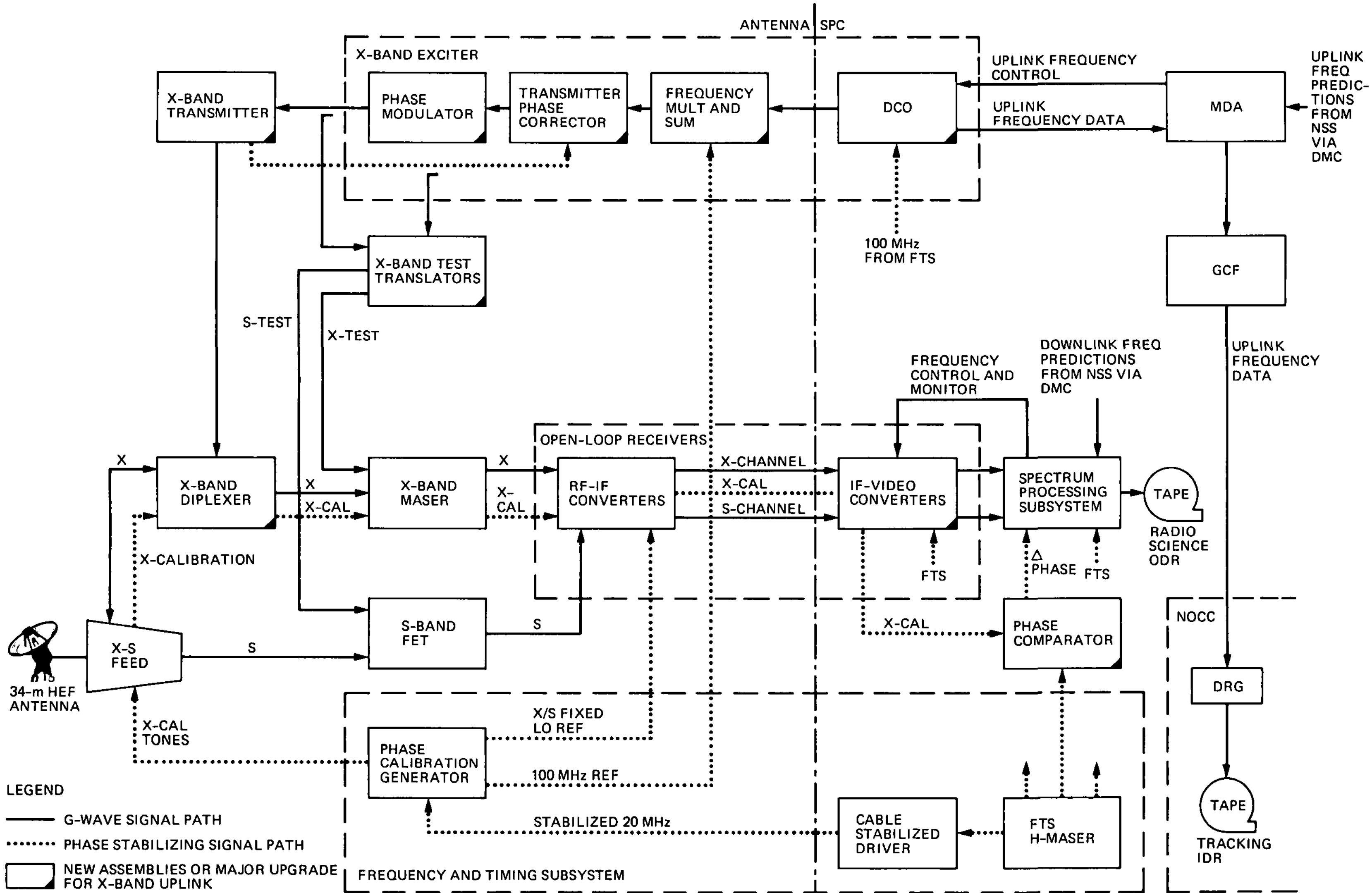


Fig. 3. Stabilized X-band signal path for the G wave experiment on the 34-m HEF antenna